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RESEARCH ON PROBLEMS OF ION BEAM FORMATION FROM ELECTRON BOMBARDMENT ION SOURCES

H. J. King, Project Engineer

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-4118

HUGHES RESEARCH LABORATORIES
A Division of Hughes Aircraft Company
Malibu, California

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SUMMARY REPORT

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ABSTRACT

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Cathode life in Kaufman type mercury electron bombardment ion thrustors has been limited by sputtering erosion caused by ions from the plasma accelerated through the cathode sheath. This contract has been concerned with the development of a cathode in which this problem is eliminated by operating the discharge in an arc mode, using the surface of liquid mercury as the cathode and utilizing the removal of liquid mercury atoms from the cathode by the discharge as the propellant feed mechanism. This also eliminates the need for a liquid-vapor phase separator in the feed system. To provide a stable equilibrium position independent of gravitational forces for the mercury surface, the mercury is forced through a porous tungsten plug or small orifice and held as a thin film or drop by surface tension forces and arc pressure. Cathodes of this design yield a ratio of electrons to atoms leaving the cathode of > 25, and they have been successfully operated in ion thrustors of the above type. Research is continuing to establish optimum operating conditions for stable efficient operation in a practical thrustor.

Author

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I. INTRODUCTION

It has been recognized for some time that the useful life of electron bombardment mercury ion thrustors depends critically on the life of the electron emitter which sustains the discharge. The initial approach has been to use a thermionic emitter to supply the necessary electrons. This suffers both from evaporation of cathode material and from sputtering damage caused by ions from the arc which fall through the cathode sheath and strike the cathode surface. Both of these processes remove cathode material and ultimately cause cathode failure. This has been summarized recently by Milder and Kerslake,[1] who conclude that existing cathodes have lifetimes which are as much as an order of magnitude less than the rest of the thrustor components.

A liquid-mercury cathode[2, 3] has been developed for which this problem is completely eliminated by operating the discharge in an arc mode, using a surface of liquid mercury as the cathode, and utilizing the removal of mercury atoms from this cathode by the discharge as the propellant feed mechanism. As an additional advantage, no separation is required between liquid and vapor phases in the feed system. To provide for an equilibrium position of the liquid mercury surface independent of gravity, the mercury is forced through a porous tungsten plug or a small orifice and held as a thin film or drop by surface tension forces and arc pressure.

At the time this idea was conceived, major problems were expected to result from the following requirements which this scheme must meet in order to be useful for practical thrustors:

1. The liquid-cathode-arc mode of the discharge must be maintained while the discharge parameters are adjusted for maximum propellant mass utilization and power efficiency.

2. To permit a high degree of propellant mass utilization, the cathode must yield a sufficiently high ratio of emitted electron current to flux of mercury atoms into the discharge chamber. Using a thermionic emitter, Nakanishi, et al.,[4] have measured propellant efficiencies as high as 99% at a value of K_e/K_a of 21.

3. The cathode design must provide for an equilibrium position of the liquid mercury surface under zero-gravity conditions.

The purpose of the first phase of our investigation had been to establish whether the above conditions can be satisfied individually. This objective had been reached at the beginning of the contract period, and the results can be summarized as follows: It was demonstrated that open-pool mercury cathodes can be used in electron-bombardment ion sources, yielding simultaneously propellant mass utilizations >80% and power expenditures (excluding magnet power) < 500 eV/ion. The open pool cathodes used for these experiments required no phase separation in the feed system, but they were not gravity independent. It was also demonstrated that gravity-independent liquid-mercury cathodes are feasible, and that they can be operated in electron-bombardment ion sources. The power expenditures were comparable to those for open-pool cathodes; however, the propellant mass utilization was much lower. The cause of this deficiency was determined, and experiments indicated that the related problems should be solvable. It was concluded, therefore, that cathodes which simultaneously satisfy all three requirements should be feasible.

The liquid-mercury cathode as presently conceived is a zero-gravity adaptation of the above mercury pool cathode. A rather sophisticated design is required, however, to assure that the dual functions of cathode and feed system are both performed with efficiency and stability. Because of this we have chosen the ratio of the rate of electron emission from the cathode divided by the rate of neutral atom emission (defined in Section II as K_e/K_a) as a "figure of merit" for cathode performance. A cathode design which could be operated stably (independent of orientation with respect to gravity) at values of K_e/K_a up to at least 20 was set as the primary goal of this program. This was achieved at about the midpoint of the contract period. The second phase of the program has been devoted to incorporating the cathode into a working electron bombardment ion thrustor.

II. CATHODE DESIGN

A. Analytical Considerations

1. Electron and Atom Emission

In the cathode concept which we are investigating, the electrons required for the ionization of the propellant in an electron-bombardment ion source are drawn from a surface of liquid mercury by operating the discharge in the liquid-pool arc mode. In order to permit gravity-independent operation, the liquid mercury surface is maintained by capillary forces and arc pressure.

When an arc terminates on a mercury pool, mercury is removed from the surface at the arc spot (because of local heating and sputtering due to ion bombardment) at a rate reported in the literature as approximately one mercury atom per eight emitted electrons.[5] Evaporation of mercury atoms from any inactive part of the cathode surface is not accompanied by electron emission, thus reducing the over-all electron-to-atom ratio. In rectifiers and ignitrons the mercury lost from the cathode is condensed on the walls and returned to the cathode pool. In the thrustor this effect is utilized to feed the propellant into the discharge chamber by simply connecting the cathode pool with a propellant tank, without requiring any separation between liquid and vapor phases in the feed system.

In an electron-bombardment ion source the current ratio

$$\frac{\text{(discharge current)}}{\text{(ion beam current)}} \equiv \frac{I_D}{I_B}$$

and the admission ratio

$$\frac{\text{(number of electrons injected into the discharge chamber)}}{\text{(number propellant atoms injected into the discharge chamber)}} \equiv \frac{K_e}{K_a}$$

are related through the propellant mass utilization

$$\eta_m \equiv \frac{I_B}{eK_a} \qquad (1)$$

(where $e \equiv$ electronic charge) and through

$$I_D = eK_e + I_i \tag{2}$$

by the equation

$$\frac{I_D}{I_B} = \frac{1}{\eta_m} \cdot \frac{K_e + I_i/e}{K_a} \tag{3}$$

where I_i is the ion current flow to the cathode and is much smaller than eK_e.

Experiments with mercury electron-bombardment sources using thermionic emitters[6] have shown that in order to make the propellant mass utilization high, I_D/I_B must be of the order of 10 to 25. Because $I_i/e \ll K_e$, this also means that K_e/K_a has to be of the same order of magnitude; this leads thus to the objective stated in the Introduction, which is to attain $K_e/K_a > 20$. Comparing this desired value with the value of about 8 quoted above for the open liquid mercury pool indicates that some improvement over the performance of the admission ratio of the open liquid mercury pool is in fact required.

Since the value of the admission ratio K_e/K_a should be high, any atom flux $K_{a,v}$ due to vapor escaping from the inactive part of the cathode surface must be kept small compared with the mercury atom flux $K_{a,s}$ due to spot action:

$$K_{a,v} \ll K_{a,s} \quad . \tag{4}$$

Because

$$K_a = K_{a,s} + K_{a,v} \quad , \tag{5}$$

we also have

$$K_{a,v} \ll K_a \quad . \tag{6}$$

Combining (1) and (6) we obtain

$$K_{a,v} << \frac{I_B}{e\eta_m} \quad . \tag{7}$$

This expression relates the permissible atom flux due to evaporation from the inactive part of the cathode surface to quantities that are known at the outset of a thrustor design project.

The atom flux $K_{a,v}$ is a function of the cathode surface area A and the absolute cathode surface temperature T; therefore, the limit on $K_{a,v}$ is to be interpreted as a limit on these quantities. For the purpose of an estimate we make the following approximate assumptions: (a) the cathode surface temperature outside the arc spot is uniform, (b) the mercury vapor leaving the cathode is in thermal equilibrium with the cathode surface, (c) this mercury vapor behaves as an ideal gas, and (d) the flux $K_{a,s}$ does not depend on the cathode surface temperature outside the arc spot. We put

$$K_{a,v} = A\,L_{a,v} \quad , \tag{8}$$

assuming the active area of cathode to be negligible with respect to A. Here L denotes a number flux density. From the gas-kinetic equations

$$L = \frac{1}{4}\, n\,\overline{v} \quad , \tag{9a}$$

$$n = p/kT \quad , \tag{9b}$$

and

$$\frac{1}{2}\, m\,\overline{v}^2 = \frac{4}{\pi}\, kT \quad , \tag{9c}$$

where

$n \equiv$ number density

$\overline{v} \equiv$ average velocity

$m \equiv$ molecular mass of the gas molecule

$k \equiv$ Boltzmann's constant,

we then find

$$L_{a,v} = p_{Hg}(T) \Big/ (2\pi m_{Hg}\ kT)^{1/2} \tag{10}$$

where $p_{Hg}(T)$ is the vapor pressure of mercury as a function of temperature, and m_{Hg} is the atomic mass of mercury. Substitution of (8) and (10) into (7) yields the expression:

$$\frac{A p_{Hg}(T)}{(2\pi m_{Hg}\ kT)^{1/2}} << \frac{I_B}{e \eta_m} \quad . \tag{11}$$

While (11) is already useful for making coarse estimates, a much more rigorous relation can be obtained if an approximate value of the admission ratio resulting from spot action alone, $K_e/K_{a,s}$, is available from previous measurements (Cobine[5] and our own later results). To make use of the approximate knowledge of $K_e/K_{a,s}$, we introduce the ratio

$$\frac{K_e/K_a}{K_e/K_{a,s}} = f \quad . \tag{12}$$

From (1), (5), (8), (10), and (12) we then obtain

$$\frac{A\ p_{Hg}(T)}{(2\pi m_{Hg}\ kT)^{1/2}} = \frac{I_B}{e \eta_m} \ (1 - f) \quad . \tag{13}$$

This equation yields an upper bound for A at a given T (or for T at a given A) if we require that the actual admission ratio K_e/K_a should not fall below $K_e/K_{a,s}$ by more than a certain percentage, or that

$$f \geq f_{lim} \quad . \tag{14}$$

An example will illustrate the importance of (13). If an ion beam current $I_B = 0.5$ A is to be generated with a propellant mass utilization $\eta_m = 0.9$ and if we set $f_{lim} = 0.95$, the maximum permissable values of the cathode surface area A (and the corresponding diameters d for circular cathodes) are determined as follows:

$$\text{at } T = 300^\circ K, \quad A \lesssim 40 \text{ mm}^2, \quad d \lesssim 7 \text{ mm};$$

$$\text{at } T = 400^\circ K, \quad A \lesssim 0.14 \text{ mm}^2, \quad d \lesssim 0.4 \text{ mm} .$$

It is obvious from these numbers that cathodes of reasonable size can yield useful values of K_e/K_a only if the cathode surface temperature is kept below 400°K.

Possible mechanisms for electron emission from the mercury surface have been summarized by Hernquist[7] and Hull.[8] From these investigations it appears that the mechanism is not defined clearly enough that a straightforward technique could be devised to improve K_e/K_a by enhancing electron emission.

In conclusion, the only straightforward means of increasing K_e/K_a is to reduce both cathode size (area of exposed mercury surface) and cathode temperature.

2. Cathode Cooling

In order to improve K_e/K_a by cathode cooling, it is of interest to estimate the amount of heat put into the cathode from ion impact and from discharge chamber radiation. The power which the ions deposit at the cathode may be estimated to first order as follows:

P_c ≡ power carried to cathode by ions, W

I_i ≡ ion current flowing from plasma to cathode, A

I_e ≡ electron current leaving cathode, A

I_D ≡ discharge current, A

I_B ≡ beam current, A

V_S ≡ voltage of cathode sheath, V

V_i ≡ first ionization potential of mercury (10.4 V).

Let us take as an example the following typical experimental conditions:

$$I_D \simeq 20\, I_B$$

$$15 \text{ V} \leq V_S \leq 35 \text{ V} .$$

Let

$$I_e = \alpha I_i$$

where α = constant >> 1. Then

$$I_e \cong I_D \quad ,$$

and

$$P_c = I_i(V_S + V_i) = 20 \frac{I_B}{\alpha} (V_S + V_i) \quad .$$

Therefore

$$P_{c_{max}} = \frac{I_B}{\alpha} (20)(35 + 10.4) = 918 \frac{I_B}{\alpha} \quad .$$

The maximum power to the cathode per ampere of beam current is $918/\alpha$. At a net beam voltage of 5000 V the maximum power to the cathode represents

$$\frac{918}{5000\,\alpha} \times 100 = \frac{18.4}{\alpha} \text{ \% of the beam power.}$$

The value of α depends on the arc conditions. The theoretical maximum is given by Bohm[9] as

$$\alpha = \left(\frac{\text{mass of mercury ion}}{\text{mass of electron}}\right)^{1/2} = 607 \quad .$$

The minimum value has been experimentally established by Hernquist[7] as approximately 50. The contribution of radiation from the discharge chamber walls may be from 0.2 to 0.4 W/cm^2 of cathode surface, depending on the exact ambient temperature attained, and is therefore negligible. Thus the power input to the cathode represent $\sim$0.3 % of the beam power, assuming the most pessimistic value α = 50, and is in fact probably no higher than 0.1%.

With the actual cathode configurations used to date, this heat input results in cathode temperatures typically of the order of 150°C. According to (4), with the typical mercury surface diameters of < 0.4 mm used in our latest cathodes, cathode temperatures between 30°C and 60°C will have to be maintained to keep evaporation tolerable. This is consistent with our measurements, which show that no appreciable improvement in K_e/K_a is gained by cooling much below 40°C.

With the heat power input to the cathode evaluated above, the "cooling power" to be supplied to the cathode will be of the order of $0.1\%/\eta_{cool}$ of beam power, where $\eta_{cool} \equiv$ cooling efficiency. Even assuming $\eta_{cool} \leq 20\%$ (for thermoelectric cooling elements, with a temperature differential of 100°C), the cooling power consumption does not exceed 1% of beam power.

B. Mechanical Considerations

1. Gravity-Independent Surface Maintenance — Basic Approaches

In order for the liquid mercury cathode to be useful in space propulsion applications, the position of the liquid mercury surface must be maintained in equilibrium without the aid of gravitational forces. This is accomplished by balancing the hydrostatic pressure under which the propellant is delivered to the free surface against the sum of surface tension forces and arc forces. Two approaches have been investigated: mercury feeding through a porous plug, and mercury feeding through a single orifice.

In porous-plug cathodes, liquid mercury is forced under pressure through a porous disc made of a refractory metal. In order to obtain a cathode area of sufficiently small size, the face of the porous plug is electron-beam "washed" (i.e., a surface layer is melted to close the pores) everywhere except within a diameter slightly smaller than the intended cathode diameter. Steady state operation of porous-plug cathodes is obtained by adjusting the mercury feed rate (through control of the feed pressure) at a fixed discharge current so that an area slightly larger than the unwashed porous plug area is covered by mercury. This results in a stable equilibrium position of the mercury surface: if the feed rate increases slightly at a fixed discharge current, the mercury-covered portion of the washed plug surface will grow until evaporation from the enlarged mercury surface area balances the increase in feed rate (and the opposite is true if the feed rate decreases slightly).

In single-orifice cathodes, liquid mercury is forced through a capillary tube, an annular slit, or a divergent nozzle. A small mercury globule is made to form at the orifice, and the arc is struck from this globule. A stable equilibrium position of the mercury surface always exists for the divergent nozzle configuration, and the area of the free mercury surface increases if this surface shifts downstream; therefore, the same argument as in the last paragraph applies. In the case of a uniform cross section configuration (such as a capillary tube), the equilibrium of the mercury surface position can be stable or is only neutral, depending on whether the free mercury surface is kept inside or outside the uniform cross section region. Outside, the same situation as in the porous-plug case prevails, resulting in stable equilibrium. Inside, however, equilibrium of the surface position is neutral, and maintaining the mercury surface stationary in this case requires considerably more accurate adjustment of the feed rate (or the discharge current).

In practical applications of liquid-mercury cathodes it will be necessary to sense the position of the free mercury surface, and to feed this information into a control circuit linking feed rate and discharge current. The required accuracy of the sensing method would be most stringent in the case of neutral equilibrium of the surface position. An example of a sensor which should be applicable to a divergent nozzle as well as a uniform cross section configuration (if the free mercury surface is kept inside the uniform cross section region) consists of an annular thermocouple junction surrounding the orifice close to the intended downstream limit of the mercury surface position. By careful thermal design of the cathode configuration, the temperature in this location may be made to increase if the mercury surface shifts upstream, thereby generating the desired sensor output.

2. Compatibility of Materials with Liquid Mercury

Because many metals tend to amalgamate with mercury, the possible candidates for use as metallic support structure containers and dispensers are restricted to a few metals.[10] We have limited our use to the following: tungsten, molybdenum, stainless steel, and titanium. Neoprene, butyl rubber, and teflon gaskets and O-rings are likewise unaffected by the applications described herein.

3. Mechanical Design

For an initial evaluation, porous tungsten plugs were judged to be usable for mercury dispensers. An existing 3/4 in. diameter porous plug 0.050 in. thick, welded to a 3/4 in. long molybdenum sleeve, was fitted with a small piston and sealed with a neoprene O-ring. A screw thread drive provided either direct or spring pressure drive upon the piston. Such a simple unit confirmed the concept that zero G operation was feasible with an arc operating from a liquid mercury surface. This was shown by operating the cathode upside down (i.e., the cathode face horizontal and facing down) for several minutes. It also allowed operation with the face horizontal and facing up for 30 min.

Poor control of the mercury feed rate as well as the need for a larger mercury reservoir to allow for longer runs led to the following design. A porous tungsten plug (with 2 μ mean pore size) 1/4 in. in diameter and 0.040 in. thick was electron beam welded to a molybdenum adapter. This was welded to a titanium tube which led to a larger spring pressure feed system. This cathode furnished the results which were judged to be complete evidence of feasibility of the liquid mercury cathode. Operating with the face vertical, the cathode ran stably in a diode arc mode for the full length of time (75 min) allowed by the reservoir size. Excellent control of the mercury film on the face of the cathode was achieved. At any time it was possible to allow the film to be used up by arc action or to regain full film condition merely by proper feed adjustment.

Different plugs from 2 to 10 μ pore size were evaluated. These tests indicated that the 4 μ pore size generally available gave sufficient control of the mercury flow.

Later porous plug designs were fitted with a clamp-on cooling jacket. These plugs gave the first encouraging results, providing K_e/K_a values of 10 to 12 and once as high as 19 for several hours. The size of the mercury droplet on the plug was poorly defined, however, and on occasion several small drops would form at various points and the arc would jump from point to point.

Other plug materials were also tried. Porous graphite and felted nickel fibers showed arc starting and amalgamation difficulties, respectively. Porous molybdenum also showed harder arc starting; titanium evidenced harder arc starting than molybdenum and was discarded.

A serious difficulty with the porous plugs was the formation of craters on the plug surface if attempts were made to sustain an arc with insufficient mercury coverage. Apparently the arc would strike the plug itself and consume part of the porous material.

This difficulty led to the consideration of single orifice cathodes to produce a single confined mercury droplet of reproducible size. The first single orifice cathode consisted of an annular orifice formed by fitting a tapered pin in a conical hole. The pin was axially adjustable with a micrometer screw. It was found that for satisfactory operation the adjustment was extremely critical, and machining tolerances of less than 0.001 in. were required. One annulus was satisfactorily operated at a K_e/K_a value of 7.7; however, mechanical problems made the design impractical. Therefore, this approach was abandoned in favor of a single small round hole. A simple orifice was made by spark eroding a hole 0.0015 in. in diameter in a molybdenum block. The arc end of the hole was counterbored to 0.060 in. diameter to provide a reservoir for the mercury. The impedance of even this small hole was too low to permit adequate control of the mercury flow with the available feed systems. The mercury flow impedance of the orifice was then augmented with a needle valve adjusted by a micrometer screw, and stable K_e/K_a values of ~ 10 were again attained for periods of several hours. Adjustment of this mechanical impedance was also too complex, however. It was noted that no pitting occurred on either the annulus or orifices during the starting or stopping of the arc.

Assessment of the results to this point led to the current design. In this design, the mercury flow impedance was separated from the aperture which defines the mercury surface. The most logical step seemed to be to place a porous tungsten plug as a separate impedance immediately upstream of the orifice. It was decided to terminate the orifice on the arc (downstream) side with a conical rather than cylindrical counterbore, thus permitting adjustment of the area of mercury exposed to the arc. This conical aperture gives an inherently stable geometry since there is one particular position where the exposed mercury area is of the correct size for a given set of arc conditions. A cylindrical counterbore or simple orifice does not have this property. The exposed area of the cylindrical hole is optimum for only one particular current, and the area does not change with axial position along the orifice except at the ends of the orifice. The first conical nozzle cathode built performed very well and subsequent designs which incorporate only minor changes have consistently operated at K_e/K_a values of 20 to 25 and on more than one occasion they have run at K_e/K_a up to 35. The modifications have been mainly in manufacturing technique except for a change in the counterbore angle (to provide a somewhat larger mercury reservoir and slower area change with axial position of the equilibrium surface), and a relocation of the impedance to place it between the mercury feed system and the valve rather than on the downstream side of the valve. The latter change makes the system more flexible and easier to fabricate.

Figure 1 shows the cathode-feed system configuration. The porous plug is shown near the cathode tip. The water cooling jacket is also shown. Water cooling is used here, largely for convenience, because the present cathodes are long enough (10 in.) to permit the feed system to remain outside the vacuum while the cathode projects through a vacuum seal into the arc chamber of the thrustor or test diode. Shorter cathodes designed to operate with a feed system in vacuum will use conduction cooling. For example, a 3/8 in. diameter copper bar (the diameter of the present cathode) can carry 10 W of power with a temperature drop of only $10^{\circ}C/in.$ of length.

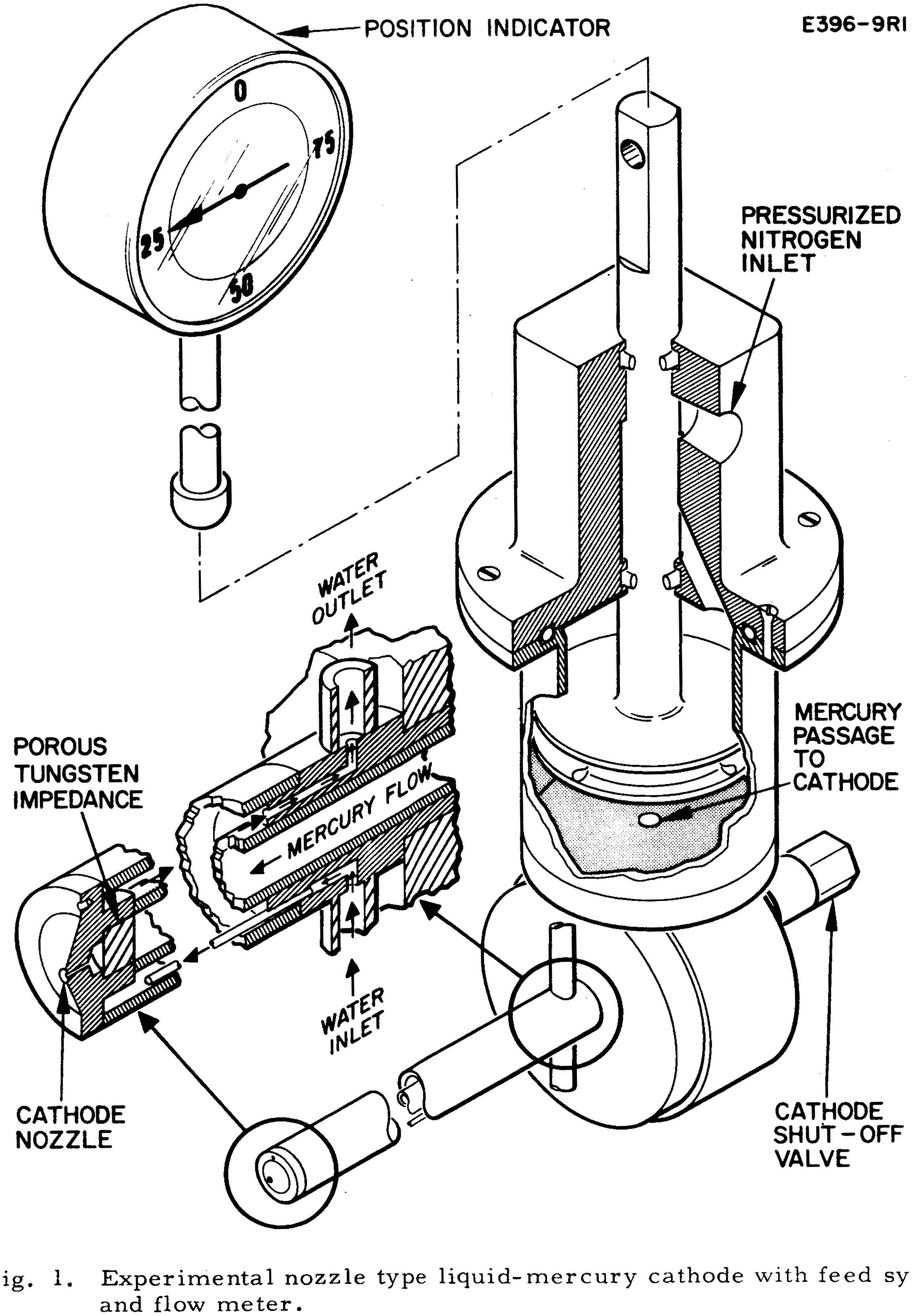

Fig. 1. Experimental nozzle type liquid-mercury cathode with feed system and flow meter.

III. FEED SYSTEMS

The initial experiments were performed with a hand operated feed mechanism consisting of a lead screw driving a piston. These systems served to demonstrate the feasibility of the cathode for short runs but were unsatisfactory for extended operation.

A pneumatic system (Fig. 1) was designed in which pressurized nitrogen was used as the driving force. Such systems have been used throughout the contract period for all experiments. The piston motion is measured with a dial indicator (calibrated to 0.001 in.) contacting the top of the piston shaft. The piston position is plotted as a function of time, and the slope of the line establishes the flow rate. Two reservoir diameters have been used to provide 1% accuracy at various flow rates. The 1.580 in. diameter piston has a calibration constant such that 0.001 in. of motion/hour equals 58.4 mA equivalent of Hg^o and the 0.215 in. diameter piston a constant so that 0.001 in. of motion/hour equals 1.1 mA equivalent of Hg^o. The largest capacity reservoir made to date holds enough mercury to operate for 785 hours at 350 mA. Other sizes can easily be made to accommodate particular requirements.

The possibility of using electrolytic action to both meter and transport the mercury has been investigated. The basic concept is illustrated in Fig. 2. The two porous membranes separate the electrolyte from the mercury column. The pore size in the membrane is chosen so that free ions can pass through them freely while the liquid mercury is constrained by capillary forces. The electrolyte-mercury interfaces are thus mechanically defined. When a voltage is impressed across the electrolyte column mercury ions are transported electrolytically in direct proportion to the current flow. By controlling the voltage it is possible to adjust the current over a fairly wide range thus such a system incorporates the features of both controlling and measuring the mercury flow. Laboratory experiments have demonstrated that mercury transport is possible, but no practical material has yet been found that will serve as the porous membrane in a final system. Because of the desirable features of this approach, it is being further investigated.

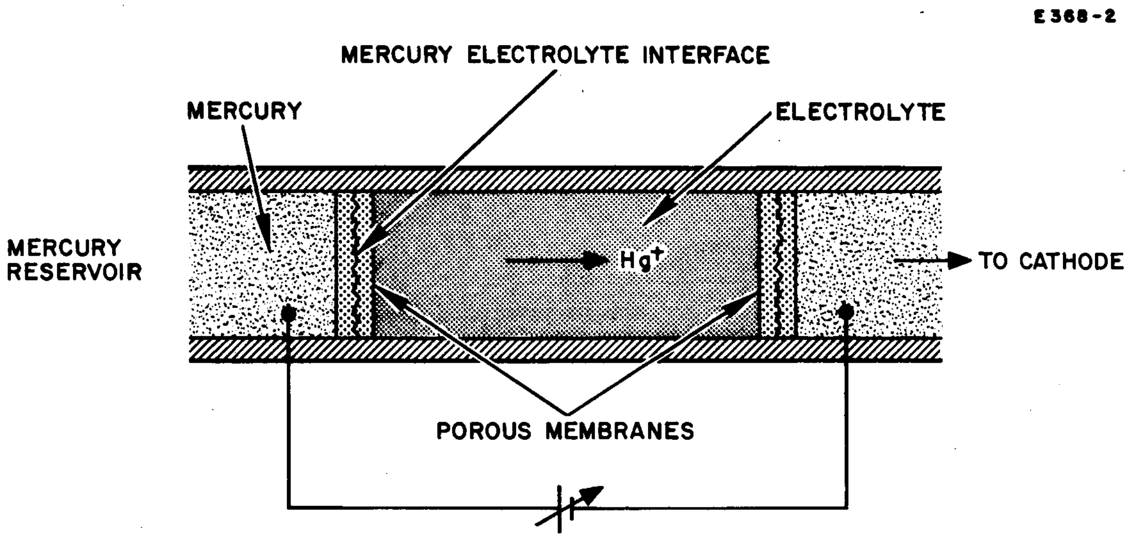

Fig. 2. Electrolytic feed system.

IV. ARC IGNITION

Two methods of arc ignition have been used: rf or dc. With the rf method, an arc is drawn from the mercury surface with a Tesla coil or other rf discharge. The arc will then transfer to the anode and the rf may be shut off. Normally very short bursts of rf are required, and ignition is virtually instantaneous. There is some evidence, however, that the repeated arcing of a rf discharge may have a deleterious effect on the cathode surface if attempts are made to start the arc when insufficient mercury is present. It is postulated that this is the cause of some of the pitting observed on the porous tungsten plugs.

For dc ignition, it has been demonstrated that the arc can be readily started by breaking a contact at the mercury surface. Since the cathodes are inserted into the vacuum system through chevron compression seals, they are movable in the axial direction. The arc may be ignited by applying voltage between cathode and igniter with a series resistor in the circuit to limit the current when contact is made. The cathode is pulled back and the arc ignites when contact with the igniter is broken. A simple mechanical design has been proposed which would accomplish this movement by the heating of a bimetal strip.

Other ignition techniques and mechanisms have been summarized by Cobine.[5] They have not been pursued under the present contract because the above two mechanisms have fulfilled present requirements.

V. EXPERIMENTAL RESULTS OF CATHODE TESTS

In the early phases of the program, the majority of the cathode tests were done in a simple diode at pressures of approximately 10^{-5} Torr. Final tests have been in ion thrustors of the Kaufmann type having diameters of 6.5 and 10 cm. The latter have been operated both as Penning discharges without ion extraction, and as true ion thrustors with ion beam extraction at voltages up to 5 kV. Operation has been successful in all respects, although the thrustor has somewhat different characteristics when operated with a simple thermionic emitter where the propellant feed rate, arc current, and arc voltage can all be adjusted independently from each other.

A. Diode Tests

The diode test station in which the preliminary cathode tests were conducted consisted of a 6 in. diameter pyrex cross pumped by a mercury diffusion pump equipped with liquid nitrogen baffles. The arms of the cross were used to mount the pump, the anode, the movable igniter electrode, and the plate holding the cathode and necessary electrical feedthroughs for thermocouples, probes, etc. Arc voltage was supplied from a current limiting power supply through an adjustable (0 to 5Ω) resistor. The resistor compensated for the negative arc resistance to be discussed later. The current limiting feature of the supply was desirable because of the interdependence of the arc current and voltage. With such a supply enough voltage is automatically provided to draw a predetermined current, thus allowing long term operation at a constant K_e/K_a once the mercury feed rate has become stable. This feature permits extended operation at arc currents just below the limiting current at which the arc will extinguish. No magnetic fields were applied during these diode tests.

All cathode configurations described in Section II were first tested in this station. The tests were straightforward and consisted simply of slowly increasing the K_e/K_a by appropriate adjustment of the mercury flow and discharge current. Table I is a summary of the significant data so obtained and Fig. 3 indicates the effect of cathode temperature on K_e/K_a for the various geometries. The final diode test was a 24 hour run of the 4N cathode described in the next paragraphs.

Cathode 4N was of the nozzle type, with conical nozzle and integral cooling geometry shown in Fig. 1 and with water jacket cooling. The porous tungsten plug (4 μ Firth Sterling) was in the downstream position just ahead of the cathode orifice.

TABLE I

Summary of Diode Tests

Date	Cathode Type			Current, A	Run Duration, Hours	K_e/K_a
	Geometry	Size	Cooling			
Prior to start of contract	porous tungsten	3/4 in.	no	3.0	0.5	
	porous tungsten	3/4 in.	no	3.2	1.25	
	porous tungsten	3/4 in.	no	2.9	2.4	0.74
	porous tungsten	3/4 in.	no	3.0	11.5	0.50
1/10/64	porous tungsten	washed to 1/16 in. dia.	no	3.0		1.8
2/14/64	porous tungsten	washed to 0.030 in. dia.	yes	5.5	6.0	8.0
2/18/64	porous tungsten		yes	5.0	5.0	19.0
2/26/64	annular orifice	0.066 in. dia.	yes	3.7	3.2	7.7
3/16/64	round orifice	0.0015 in. dia.	no	3.0		1.1
	round orifice	0.0015 in. dia.	yes	3.0	4.0	7.5
3/20/64	porous tungsten 10μ pores	0.030 in. dia.	yes		0.5	10.5 in Penning cell
4/20/64	final design described above	nozzle	yes	1.5	0.75	11.7
5/26/64	final design described above		yes	6.0	25.0	19.0
	final design described above		yes	9.0	0.2	37.0

This cathode was placed in the test diode. The K_e/K_a was slowly increased to 20 at 3:30 p.m. Small Hg^o flow fluctuations reduced this to K_e/K_a = 19 by 9 p.m. This point was maintained until 1 p.m. the next day. The arc extinguished once during this period (it was re-started in less than 1 min); otherwise it remained completely stable and required no adjustment. There was no stabilizing circuitry or feedback loop except the current limiting feature of the supply. Table II defines the test point.

After approximately 24 hours it was decided to terminate the test. Rather than simply shutting off the supply the current was increased at approximately 1 A/10 min (with constant feed rate), thus increasing

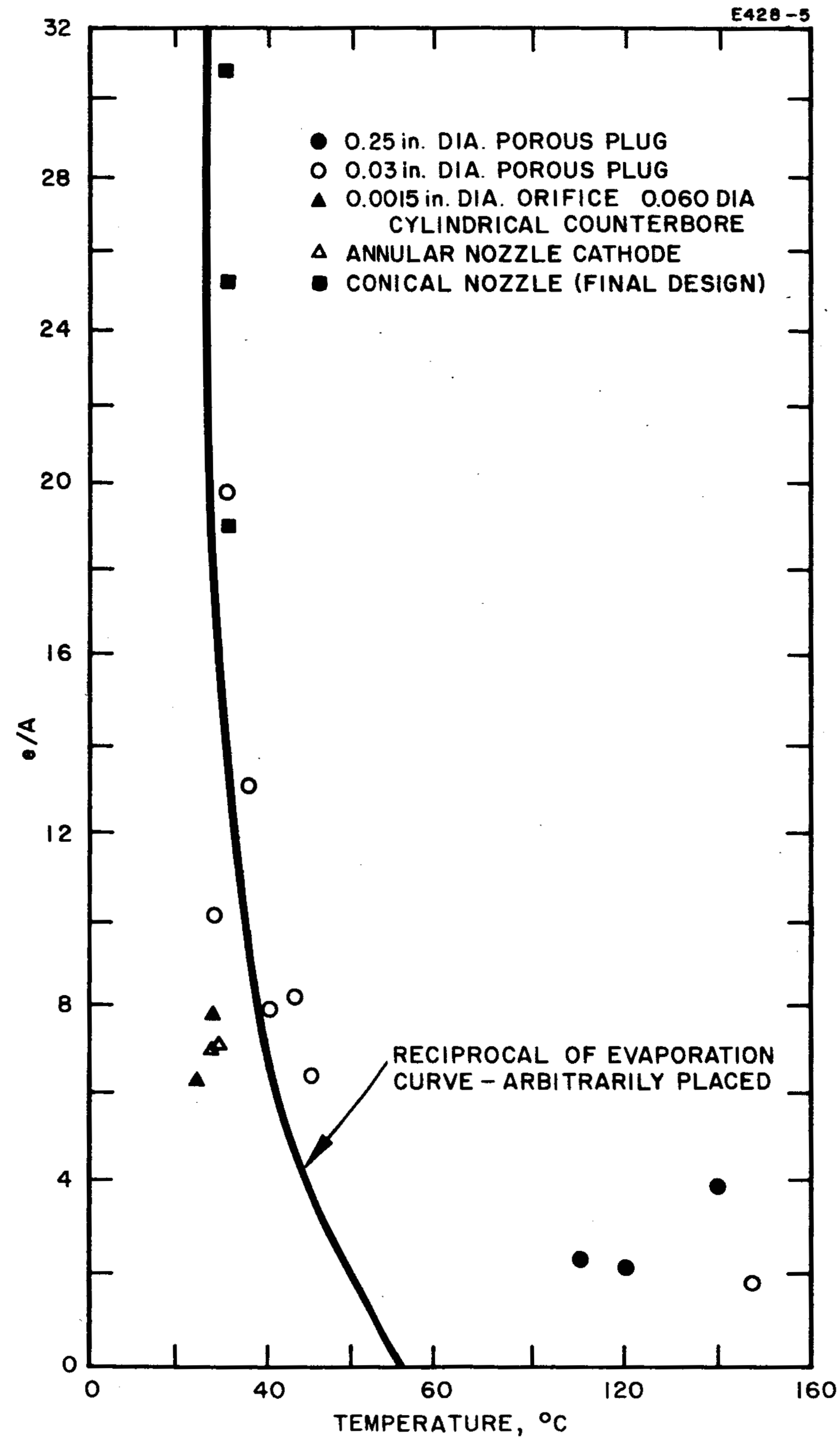

Fig. 3. Effect of cathode temperature on K_e/K_a

TABLE II

24-Hour Test Point

Cathode	4N
Discharge current, A	5.6
Hg^o feed rate	
-piston motion, in./hour	0.0050
-equivalent amperes of Hg^o	0.290
K_e/K_a	19.3
Temperature of cathode tip, ^oC	27
Vacuum, Torr	9×10^{-6}
Duration, hours	23
Reason for termination	test purposely stopped

K_e/K_a. The arc finally extinguished at 9.0 A, with a corresponding value of K_e/K_a of 31. Since the conical aperture is so small that the mercury stored there will sustain the arc for approximately 1 sec, this high K_e/K_a cannot be attributed to simply using up mercury already at the cathode tip. It thus represents true cathode operation at this point. The mercury valve was closed overnight and the cathode left in the vacuum station. The arc was started the next morning and immediately came to a K_e/K_a of 20.

During the period where the arc current was being increased prior to shutdown of the life test, a plot of cathode current versus discharge voltage (see Fig. 4) showing the negative resistance characteristics of the arc was obtained. For this particular geometry the arc resistance is -1Ω. This correlates with the fact empirically discovered during the life test that a series resistor of 1.5 to 2 Ω was required for stable arc operation. When operated in a Penning discharge mode as in the thrustor, the magnetic field increases the arc impedance to a positive value as shown in Fig. 5.

Upon completion of this test, emphasis was placed on integrating the cathode with the thrustor.

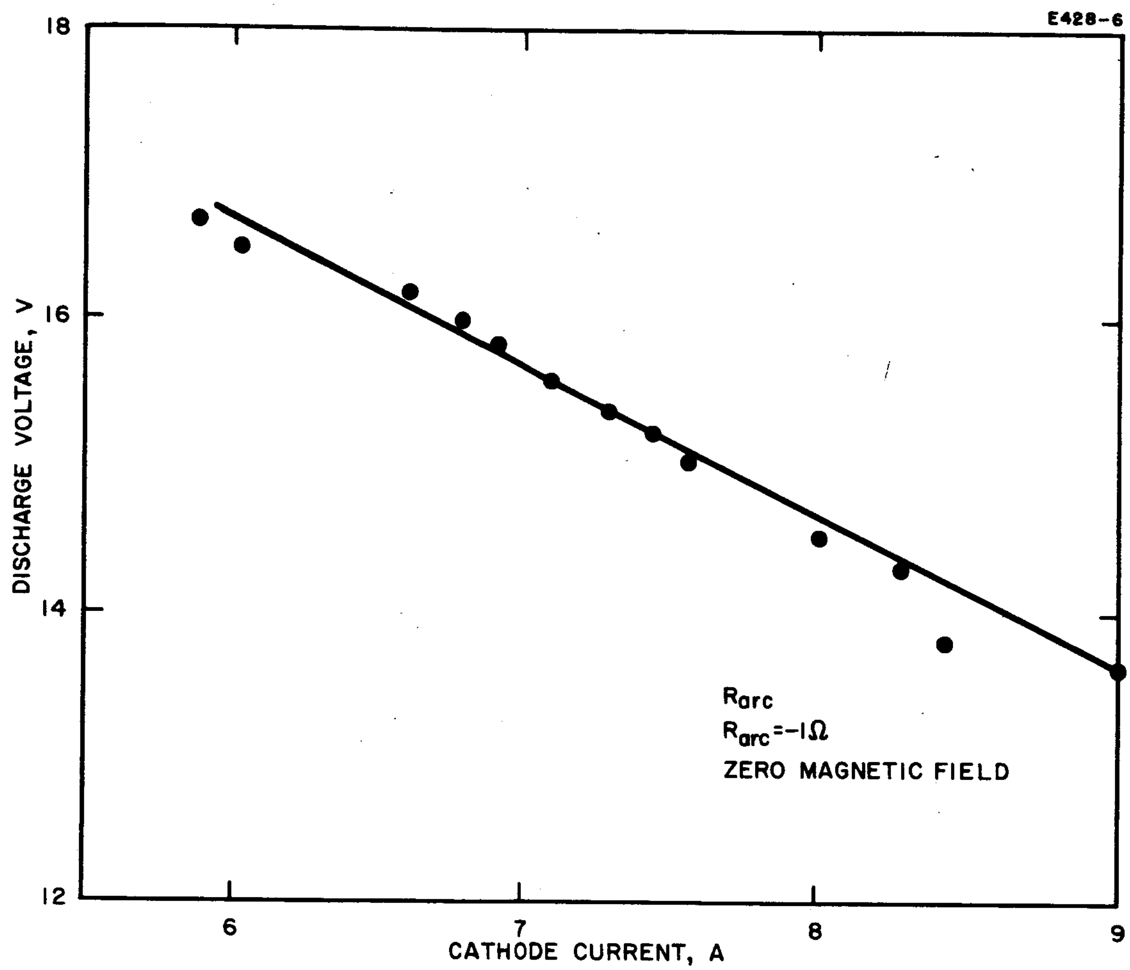

Fig. 4. Cathode current versus discharge voltage in diode without magnetic field.

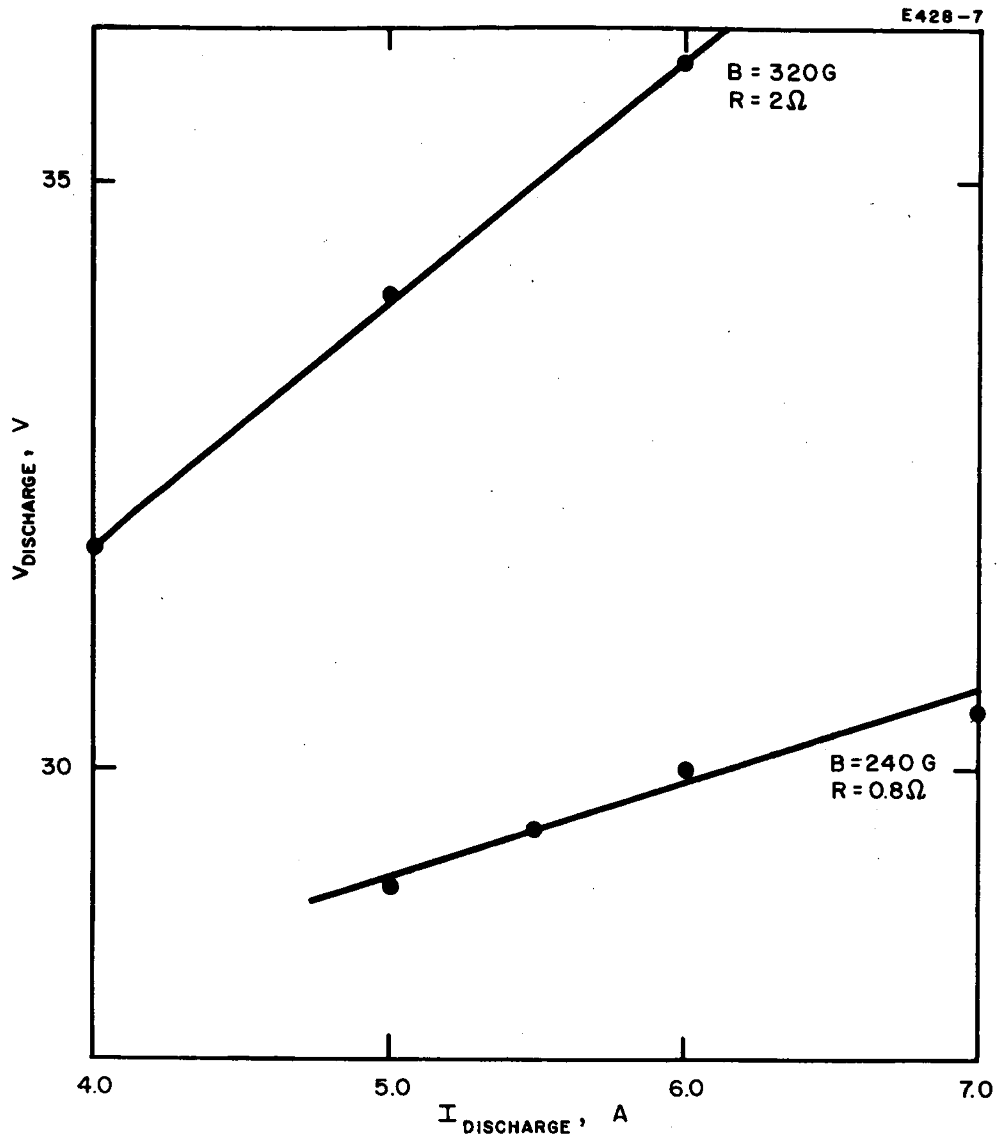

Fig. 5. Cathode current versus discharge voltage in thrustor with magnetic field.

B. Thrustor Tests

1. Open Pool Cathode

Prior to the start of the contract it was established that an open pool mercury cathode could be used in conjunction with an electron bombardment type ion source useful for ion beam production. This open pool geometry of course would not operate in zero gravity, but it did exhibit adequate performance to justify development of a gravity independent system.

The apparatus used was designed for a wide range of all operating parameters. A cylindrical 6-cm diameter discharge chamber was mounted inside a pair of water-cooled Helmholtz coils capable of producing fields up to 1.5 kG on the axis. The discharge chamber could be mounted with its axis either vertical or horizontal. The cathode consisted of a mercury meniscus inside a quartz tube of 5 mm inner diameter; a tungsten spiral could be inserted in this tube to serve as a spot anchor. One end of the tube protruded through the upstream end plate of the discharge chamber, the other end was connected to a mercury flow meter and a barometric feed system. Horizontal mounting of the discharge chamber required a 90^{o} bend in the quartz tube to keep the mercury surface horizontal. The behavior of the discharge was found to be unaffected by this bend. Accelerator and screen electrodes of the ion extraction system consisted of two parallel grids made of cylindrical tungsten bars. The ion beam was collected by a conical, water-cooled target, surrounded by a cylindrical, liquid-nitrogen-cooled shroud; this arrangement kept the mercury vapor pressure measured 40 cm downstream from the accelerator electrode within the range 5×10^{-6} to 5×10^{-5} Torr for collector currents of 75 to 800 mA. Typical ranges of the experimental results obtained with this apparatus are given in Table III.

TABLE III

Parameter Ranges for 6-cm Diameter Electron-Bombardment Ion Source with Open-Pool Liquid-Mercury Cathode

Discharge current, A	2.5 to 30
Discharge voltage, V	30 to 55
Magnetic field, G	200 to 1200
Beam current to collector, mA	75 to 800
Admission ratio (K_e/K_a)	7.5 to 11
Propellant mass utilization, %	38 to 87
Power expenditure (excluding magnet power), eV/ion	460 to 1600

A propellant mass utilization $> 80\%$ was obtained simultaneously with a discharge chamber power expenditure < 500 eV/ion. The conclusion drawn from these measurements is that a properly sized open-pool liquid-mercury cathode does perform satisfactorily in an electron-bombardment ion source configuration, as it was expected from the known characteristics of the classical mercury pool discharge.

2. Gravity Independent Cathodes

Gravity independent cathode tests in a thrustor were deferred until the final phase of the contract period so that as many of the cathode problems as possible could be solved without adding the complexity of the high voltage associated with thrustor operation. For this reason the test data are not extensive, but they are adequate to illustrate two points: (1) a gravity independent cathode can be made to operate stably in a thrustor producing an ion beam: (2) a simple substitution of a liquid mercury cathode for a thermionic emitter in a conventional Kaufman type thrustor does not produce an optimum configuration, and further integration and optimization effort is required.

The test thrustors available were 6 cm and 10 cm in diameter. The smaller was a modification of the design discussed above, with magnet coils mounted external to the vacuum system. The most notable feature of this design is that magnetic fields greater than 1 kG could be sustained. The second (10-cm) thrustor was of more conventional design[11,12] with optics consisting of a matrix of holes. It had been previously operated with a thermionic emitter and produced typical results[11,12] (i.e., beam currents to 300 mA at engine efficiencies of $\sim 70\%$). Both thrustors were on hand at the start of the contract.

Early attempts to operate a porous tungsten plug cathode in a thrustor at low values of K_e/K_a failed because the high mercury feed rates (and subsequent high background pressures) prohibited the application of high voltage to the accelerator electrode. As soon as nozzle type cathodes (similar to the 4N discussed above) were availabe, a stable arc could be maintained in the engine and high voltage could be applied.

The thrustor operation was similar to that of the open mercury pool cathode because high magnetic fields (> 250 G) were required for satisfactory propellant utilization. As the magnetic field was increased, the voltage required to maintain the discharge at a particular current rose from 10 V (at $B = 0$) to 40 V (at $B = 500$ G). This results because of the increased arc impedance associated with the high magnetic field. Because the cathode cannot be operated emission limited (as a thermionic emitter can), it is very difficult to separate the effect of the higher discharge voltage from that of the increased magnetic field (the voltage cannot be changed independently from the magnetic field).

Because of the high magnetic field requirements, the 6-cm source was first used to investigate cathode performance in an engine. The arc could be operated stably and a beam extracted for short periods of time before high voltage breakdown would initiate a large enough transient to extinguish the arc. Although the arc could be immediately restarted and the point re-established, no data were obtained with the 6-cm thrustor that fulfill the contract requirement of 30 min of stable operation. However, a few data points for this design are included in Table IV to illustrate these preliminary results, and because they are consistent with later results. In each case the Hg^{o} flow was maintained constant for more than 1 hour before extraction was attempted and the arc had been operated long enough to assure that no mercury was condensing in the arc chamber. These data are therefore believed to be meaningful. The beam was extracted in each case for a few minutes.

The 10-cm engine originally had a maximum magnetic field capability of $\sim$ 100 G. Initial experiments showed stable operation but maximum propellant efficiency of $\sim$ 20%. This was attributed to the low field, so additional coils were added to increase the field to $\sim$ 500 G continuously and 700 G for short periods.

Small baffles were added to the arc chamber in both the 6-cm and 10-cm engines. They were placed on an axis immediately downstream from the cathode in an attempt to diffuse any stream of neutral particles or fast electrons which might be emitted perpendicular to the cathode face. There was a definite improvement in operation with such baffles in place, although the exact shape of the baffle did not appear important.

With this geometry it was possible to reproducibly establish values of K_e/K_a of 20 or more at arc currents of 2 to 6 A in the 10-cm engine. The discharge was stable in fields up to 500 G and under all but severe high voltage arcing.

The test circuit is shown in Fig. 6. The thrustor was operated at high voltage and the beam extracted 300 V negative with respect to the grounded collector in order to prevent secondaries from the collector from entering the arc chamber. The meter I_B measures the total ion current leaving the source (plus any secondary electrons produced by ion interception on the accelerator). It is thus a better measure of arc chamber performance than the beam current which actually leaves the engine (I_c + I_y), since a poor optical system enhances the accelerator drain current (I_A) and reduces the extracted beam accordingly. Assuming that the optical system has sufficient perveance to handle the extracted beam, I_A is small and $I_B \rightarrow (I_c + I_y)$ which is the sum of collector and wall currents.

A compilation of the thrustor data obtained with both the 6-cm and 10-cm thrustor is given in Table IV.

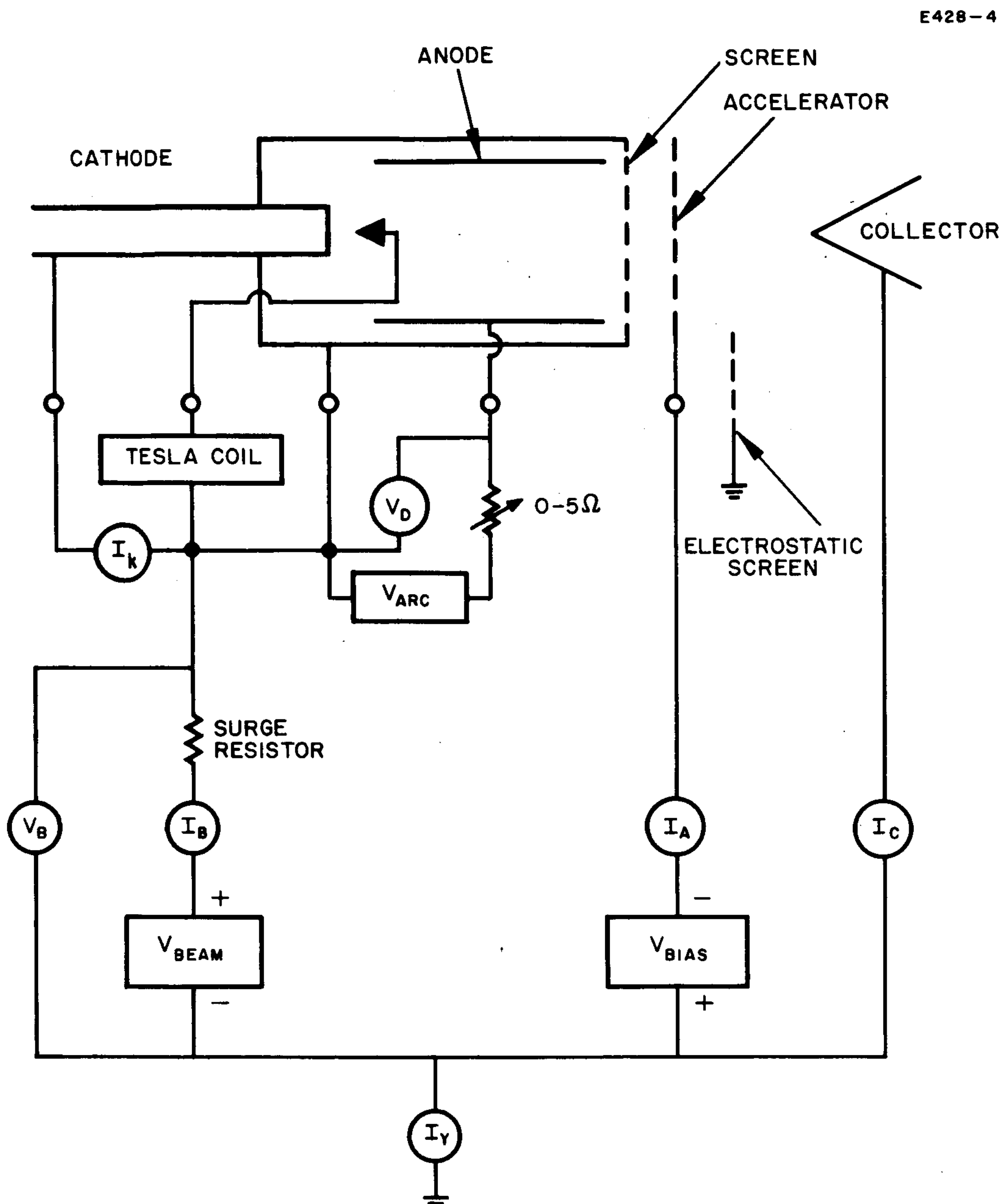

Fig. 6. Thrustor test circuit.

TABLE IV

Thrustor Performance Data

Beam Parameters					Arc Parameters						Time		Efficiencies	
I_{beam} mA	V_{beam} kV	I_{accel} mA	I_{sp} sec	$I_{extracted}$, mA	I_D A	V_D V	Magnetic Field, G	Hg^o Feed Ratio, mA	K_e/K_a	Anode Diameter, cm	Duration of Discharge Prior to Extraction, min	Duration of Extraction, min	$\eta'_{mass} = I_B/eK_a$, %	eV/ion
68	5.0	3	7100	65	2.0	39	730	115	17.3	6	60	5	59	1150
70	5.5	4	7400	64	2.0	40	840	72.5	27.7	6	45	5	94	1150
80	—	—	—	—	3.5	—	560	136	25.6	6	180	5	59	—
75	3.5	4	5900	71	3.5	39	170	137	25.5	10	120	$\boxed{47}$	55	1820
60	1.4	25	3800	35	3.4	28	130	137	24.8	10	45	$\boxed{31}$	44	1590
105	3.0	15	5500	90	3.2	34	240	169	18.9	10	180	7	62	1210
130	3.0	22	5500	108	3.9	30	240	169	23.0	10	200	3	77	1080

The dependence of thrustor performance on magnetic field is shown in Figs. 7 and 8. Figure 7 shows a linear increase in discharge voltage (for the 10 cm thrustor) with magnetic field up to 40 V at 500 G. Observe that a voltage of 40 V is typical of the voltages required with a thermionic emitter in a similar device, for good expellant utilization efficiency η_m.

Figure 8 shows the variation of propellant efficiency with axial magnetic field strength and K_e/K_a. The data shown for the 10 cm engine are a composite of data from several runs. The three points for the 6 cm engine listed in Table IV are shown for comparison. Note that, as expected, the propellant efficiency increases with K_e/K_a (arc power) for a given magnetic field and also that the propellant efficiency increases with magnetic field for a given K_e/K_a. The latter is also quantitatively reasonable since increasing the magnetic field increases the arc voltage and hence the arc power for a given discharge current. Although fewer data points are available, it is interesting to note that the 6-cm engine follows the same pattern but at a higher magnetic field. Experiments are continuing for the investigation of these phenomena both in the thrustor and in separate discharge chamber experiments.

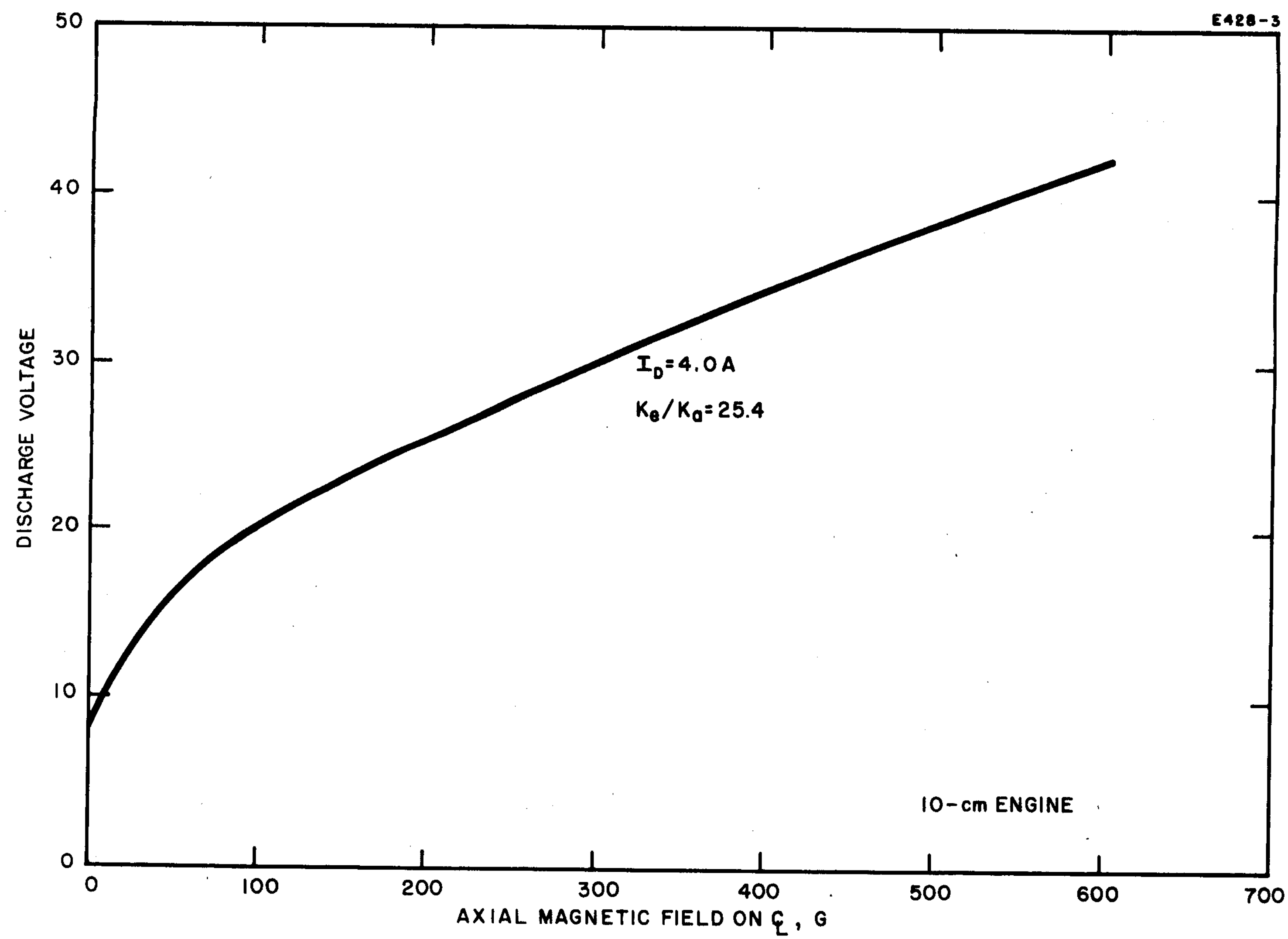

Fig. 7. Discharge voltage versus magnetic field (10 cm thrustor).

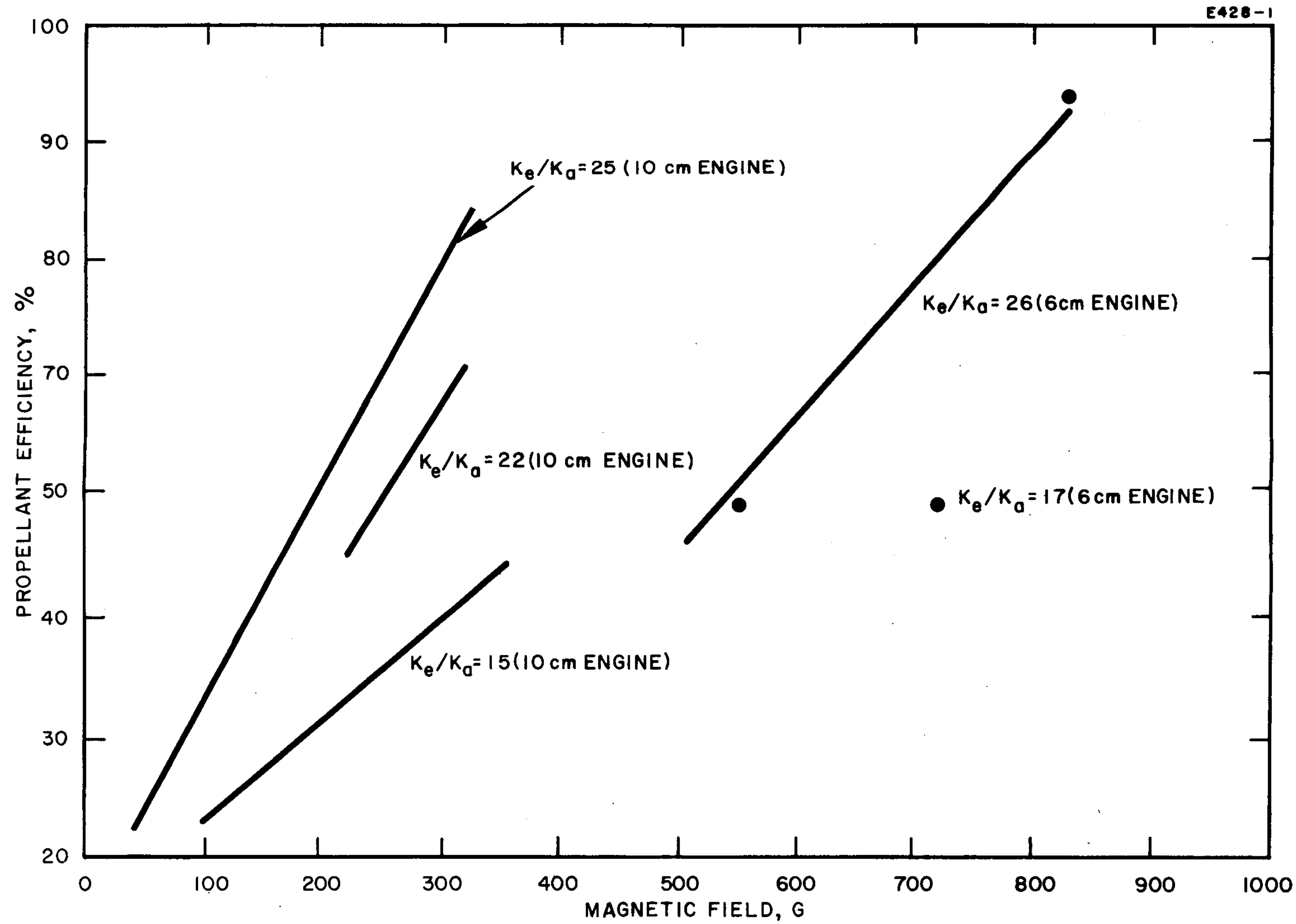

Fig. 8. Propellant field efficiency versus magnetic field and K_e/K_a.

VI. CONCLUSIONS AND RECOMMENDATIONS

A liquid mercury cathode has been designed which has the advantages of long life, low power consumption, mechanical simplicity and no phase separation in the feed system. The cathode has proved to be compatible with Kaufman type electron bombardment ion thrustors and has been used as the electron and propellant feed source in such a device, producing ion beams up to 150 mA at reasonable power and propellant efficiencies.

The performance to date has been sufficiently encouraging to warrant further development of this device. It is recommended that at least the following areas be pursued in the immediate future:

1. The cathode should be operated in a prototype thrustor to optimize its operating conditions, and to determine the measurable parameters to be used as inputs for a control circuit to stabilize operation at one point.

2. A control loop based on the above information should be constructed to aid in the evaluation of the long term operating characteristics of the device.

3. Extended life tests should be conducted to allow accurate estimates of the ultimate life capabilities and failure modes of the system. Such information should be collected as soon as possible so that any necessary design changes can be made.

4. Since no phase separation is required in the feed system for this device, it is inherently simpler than the vapor feed systems now under design elsewhere. It will be necessary, however, to consider the various possible types of liquid feed systems, to decide which is most suitable for this application and to design a suitable unit.

5. The discharge should be studied to establish the basic mechanisms controlling the ion generation and plasma density distribution in the arc chamber.

VII. INVENTIONS AND NEW TECHNOLOGY

The invention disclosure describing the zero-g liquid mercury cathode[2] has been reported to NASA. During the period of the present contract the concept has been developed to a piece of functional hardware and its performance demonstrated in an ion thrustor. The design has been improved by shaping the nozzle to a conical form and by separating the flow impedance from the capillary which supports the mercury surface.

Systems which meter and transport mercury by electrolytic action have been invented and patent disclosures[13, 14] will be reported. The feasibility of such a system has been experimentally demonstrated, but it has not yet been reduced to a functional piece of hardware.

CONTRIBUTORS

Dr. W. O. Eckhardt – originally invented the liquid-mercury cathode and demonstrated its feasibility in an electron bombardment thrustor. Dr. Eckhardt has contributed as a consultant during the present contract period.

Dr. H. J. King – project engineer.

Dr. R. C. Knechtli – department manager.

Mr. J. A. Snyder – responsible for many aspects of the design, fabrication, and testing of the cathode.

Mr. G. Saran – has aided in the collection and analysis of thrustor performance data.

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